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# CHAOS-BASED TOA ESTIMATOR FOR DS-UWB RANGING SYSTEMS IN MULTIUSER ENVIRONMENT

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## ABSTRACT

In this paper, we present a chaos-based decoupled multiuser ranging (DEMR) estimator for multiuser DS-UWB ranging system. In the DEMR estimator, users are decoupled by the knowledge of all the users' limited number of data bits. Then, the ranging performance of each user mainly depends on the non-cyclic autocorrelation property of the spreading code. Based on this property, we improve DEMR estimator by using the selected binary chaotic sequences instead of the Gold sequences in order to increase the system capacity and to improve the ranging accuracy. Simulations in CM1 channel show that the chaos-based DEMR estimator is quite near-far resistant and achieves a noticeable ranging accuracy even in a heavily loaded system. Compared with using Gold sequences, chaos-based DEMR not only works with more users than full load of Gold sequences but also improves the ranging accuracy especially under low SNR condition.

**Index Terms**— chaos, multipath channel, multiuser interference, time of arrival (TOA) estimation, Ultra-wideband (UWB).

## 1. INTRODUCTION

Ultra-wideband (UWB) technology is considered as one of the most potential candidate for indoor localization application due to their extremely large bandwidth. Time Of Arrival (TOA) measurement is most suitable for UWB signals by acquiring the distance between transmitter and receiver from the travel time of signals [1] [2].

In multiuser environment, each user is assigned a unique spreading sequence in direct-sequence ultra-wideband (DS-UWB) systems. At the receiver side, in order to separate the transmitted signals of each user, those spreading sequences should be perfectly orthogonal with each other. However, the major concern of DS-UWB system is the imperfect orthogonality of spreading code which causes multiuser interference (MUI). This problem is worsened when the system is full-loaded or the interferers are sufficiently powerful, which is known as the *near-far* problem.

Tracking of the leading edge has been challenged due to the presence of MUI. Signals from the multiple users may

interfere with the signal of desired user and deteriorate the TOA estimation drastically. Various TOA estimation algorithms [3–7] have been proposed to mitigate the MUI. [3–5] employ the classic pseudo-noise (PN) sequences as spreading sequences and mitigate the MUI through additive procedures in the receiver side. [6] designed a specific training sequence for synchronization. In [6], except assigning a spreading code to each user, a set of short length data bits in special training pattern is assigned to the user of interest. For the user of interest, MUI is mitigated due to that set of known data bits. However, [3–6] are proposed for a small number of users. In the case of heavy or fully loaded system, especially with the near-far effect, these algorithms cannot achieve acceptable performance.

Recently, [7] proposed a low complexity decoupled multiuser ranging (DEMR) TOA estimator. The DEMR estimator working in a sub-Nyquist sampling rate is quite near-far resistant and allows the system to be fully loaded due to the knowledge of the spreading sequences and a limited number of transmitted data bits for all the users [7]. In DEMR estimator, after decoupling different users by the known data bits, the ranging performance of each user mainly depends on the non-cyclic autocorrelation of the spreading sequence. Although DEMR estimator in [7] can mitigate MUI quite well, the use of classic Gold sequences limits the number of users and further improvement of ranging accuracy.

Over the past decade, chaotic spreading sequences have received significant attention due to a number of attractive features. Chaotic sequences are aperiodic, deterministic, and random-like sequences derived from nonlinear dynamical systems. Chaotic sequences' good autocorrelation and low cross-correlation properties make them particularly resistant against multipath fading and capable of mitigating the MUI [8]. Due to the high sensitivity to the initial conditions, a larger number of chaotic spreading sequences can be easily generated for increasing the system's overall capacity. Several papers have shown that chaotic sequences can be used as an alternative to the classic PN sequences [9–11]. [9] [10] proposed to replace PN sequences by the binary chaotic sequences generated by *n*-way *Bernoulli map* and *Ikeda map* in DS-CDMA communication systems in order to decrease the BER, respectively. In DS-UWB communication sys-

tem, [11] proposed that using  $n$ -way *Bernoulli map* based binary chaotic sequences can increase available bit rate. Cross-correlation property is considered as the criterion when selecting the chaotic sequences in [9–11].

In this paper, we present a chaos-based DEMR estimator for DS-UWB ranging systems. Since the ranging performance of DEMR estimator depends on the non-cyclic autocorrelation property of spreading sequences, we replace the Gold sequences by the binary chaotic sequences which are selected by using non-cyclic autocorrelation property as the criterion. One-dimensional (1-D) *Chebyshev map* and *Tent map* are used to generate the chaotic spreading sequences due to their comparatively low complexity. The proposed estimator can be extended to other chaotic maps such as *Bernoulli map* with the same criterion. Simulations show the chaos-based DEMR estimator not only can support more users than the system based on Gold sequence, but is also quite near-far resistant and achieves noticeable ranging accuracy even in over-loaded system. In low to fully loaded case, the chaotic sequences also outperform the Gold sequences, especially under low SNR condition.

The paper is organized as follows. In section 2, the DEMR estimator is explained in detail. In section 3, we describe the selection of binary chaotic sequences. Numerical evaluations of the algorithm are illustrated in section 4.

## 2. SYSTEM MODEL

In order to propose the chaos-based DEMR estimator, the DEMR estimator in [7] is introduced firstly. We consider DS-UWB system with  $K$  active users and binary phase-shift keying (BPSK) modulation. The transmitted signal by the  $k$ th user can be expressed as

$$s_k(t) = \sqrt{P_k} \sum_{m=0}^{M-1} d_k(m) \sum_{n=0}^{N-1} c'_k(n) p(t - nT_f - mT_b) \quad (1)$$

where  $P_k$  is the transmitted power of  $k$ th user,  $M$  denotes the number of transmitted data bits,  $d_k(m) \in \{\pm 1\}$  is the  $m$ th transmitted bit,  $c'_k(n) \in \{\pm 1\}$  is the unique spreading sequence of length  $N$  for the user  $k$ .  $p(t)$  is the UWB pulse shape with pulse interval  $T_p$ ,  $T_c$  is chip duration  $T_c \geq T_p$ ,  $T_f = N_c T_c$  is the frame duration, where  $N_c$  is the number of chips per frame.  $T_b = NT_f$  is data bit duration. Hence, the transmitted signal  $s_k(t)$  can be presented as

$$s_k(t) = \sqrt{P_k} \sum_{m=0}^{M-1} d_k(m) \sum_{i=0}^{NN_c-1} g_k(i) p(t - iT_c - mT_b) \quad (2)$$

where  $g_k(i) \in \{\pm 1, 0\}$ , the new spreading sequence  $g_k(i)$  can be seen as inserting  $N_c - 1$  "0" between each element of  $c'_k(n)$ , i.e.,

$$g_k(i) = \begin{cases} c'_k(i/N_c) & \text{if } i \bmod N_c = 0 \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

The  $K$  users' signal are sent through the multipath channel given in the IEEE 802.15.4a channel model [12]. The received signal is

$$r(t) = \sum_{k=1}^K \sum_{q=1}^{L_k} a_{k,q} s_k(t - \tau_{k,q}) + n(t) \quad (4)$$

where  $a_{k,q}$  and  $\tau_{k,q}$  denote the complex channel coefficient and the time delays of each multipath components respectively.  $L_k$  is the total number of paths of the  $k$ th user.  $\tau_{k,1}$  is the time delay of the first path of the  $k$ th user, which is also the parameter being estimated in TOA estimation.  $n(t)$  is the additive white Gaussian noise with zero mean and double sided power spectral density of  $N_0/2$ . We consider the reception of  $M$  bits, and assume the first user is the desired user.

In typical UWB ranging scenarios, the proper selection of  $T_c$  and  $N$  can bound  $\tau_{k,q}$  within a data bit interval. In the following part,  $\tau_{k,q}$  is approximated to integer multiples of chip duration  $\tau_{k,q} = p_{k,q} T_c$ ,  $p_{k,q}$  is an integer within  $\{0, 1, \dots, NN_c - 1\}$ , which is mild for ranging accuracy since  $T_c$  is in the order of one nano-second [7]. Hence, TOA estimation is equivalent to estimating  $p_{k,q}$ .

The receiver filter consists of an integrate-and-dump filter (IDF) with integration time  $T_c$  [7]. The received sequence at the IDF output  $\{r(l)\}$  can be expressed as

$$r(l) = \sum_{k=1}^K \sum_{q=1}^{L_k} \frac{1}{T_c} \int_{(l-1)T_c}^{lT_c} a_{k,q} s_k(t - \tau_{k,q}) dt + n(l) \quad (5)$$

$$l = 1, 2, \dots, NN_c$$

where  $n(l)$  denotes the zero-mean white Gaussian noise sample with variance  $\sigma_n^2$ . The received vector of the  $m$ th data bit is

$$\mathbf{r}(m) = [r(mNN_c + 1), r(mNN_c + 2), \dots, r(mNN_c + NN_c)]^T \quad (6)$$

where  $(\cdot)^T$  denotes the transpose operator, and  $\mathbf{n}(m)$  is formed by  $n(l)$  in the same way. The vector associated to sequence  $c'$  ( $n$ ) is defined as

$$\mathbf{c}_k = [c_k(1), c_k(2), \dots, c_k(NN_c)]^T \quad (7)$$

which  $c_k(l) = \frac{1}{T_c} \int_{(l-1)T_c}^{lT_c} \sum_{i=0}^{NN_c-1} g_k(i) p(t - iT_c) dt$ .

In the  $m$ th bit duration, due to the existence of  $\tau_{k,q}$ , received signal consists of  $\mathbf{a}_k^1(\tau_{k,q})$ , the end part of  $(m-1)$ th bit; and  $\mathbf{a}_k^2(\tau_{k,q})$ , the beginning part of  $m$ th bit.

$$\mathbf{a}_k^1(\tau_{k,q}) = \mathbf{P}_1(p_{k,q}) \mathbf{c}_k \quad (8)$$

$$\mathbf{a}_k^2(\tau_{k,q}) = \mathbf{P}_2(p_{k,q}) \mathbf{c}_k \quad (9)$$

where  $\mathbf{P}_1(p)$  and  $\mathbf{P}_2(p)$  denote the  $NN_c \times NN_c$  shifting matrices

$$\mathbf{P}_1(p) = \begin{bmatrix} \mathbf{0} & \mathbf{I}_p \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \quad \mathbf{P}_2(p) = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{I}_{NN_c-p} & \mathbf{0} \end{bmatrix} \quad (10)$$

and  $\mathbf{I}_p$  is  $p \times p$  identity matrix. Then the received vector can be rewritten as

$$\mathbf{r}(m) = \sum_{k=1}^K \sum_{q=1}^{L_k} \beta_{k,q} \mathbf{A}_k(\tau_{k,q}) \mathbf{z}_k(m) + \mathbf{n}(m) \quad (11)$$

$$m = 0, 1, \dots, M-1$$

where

$$\beta_{k,q} = a_{k,q} \sqrt{P_k} \quad (12)$$

$$\mathbf{A}_k(\tau_{k,q}) = [\mathbf{a}_k^1(\tau_{k,q}) \quad \mathbf{a}_k^2(\tau_{k,q})] \quad (13)$$

$$\mathbf{z}_k(m) = [d_k(m-1) \quad d_k(m)]^T. \quad (14)$$

When  $m = 0$ ,  $d_k(-1)$  is unknown. In this case,  $d_k(-1)$  is chosen to be 0, which affects little on the ranging performance. We rewrite  $\mathbf{r}(m)$  as

$$\mathbf{r}(m) = \mathbf{B}\mathbf{s}(m) + \mathbf{n}(m) \quad (15)$$

where

$$\mathbf{B} = \begin{bmatrix} \sum_{q=1}^{L_1} \beta_{1,q} \mathbf{A}_1(\tau_{1,q}) & \sum_{q=1}^{L_2} \beta_{2,q} \mathbf{A}_2(\tau_{2,q}) & \dots & \sum_{q=1}^{L_K} \beta_{K,q} \mathbf{A}_K(\tau_{K,q}) \end{bmatrix} \quad (16)$$

$$\mathbf{s}(m) = [\mathbf{z}_1^T(m) \quad \mathbf{z}_2^T(m) \quad \dots \quad \mathbf{z}_K^T(m)]^T. \quad (17)$$

Specially, we assume that user number, all users' spreading sequences and data bits are known. We also assume that  $\mathbf{s}(m)$  and  $\mathbf{n}(m)$  are uncorrelated [7].

With the received signal in (15), the Maximum Likelihood (ML) estimation gives a  $(1/\sqrt{M})$ -consistent estimation  $\hat{\mathbf{B}}$  of  $\mathbf{B}$  [7]:

$$\hat{\mathbf{B}} = \mathbf{R}_{\mathbf{sr}}^H(M) \mathbf{R}_{\mathbf{ss}}^{-1}(M) \quad (18)$$

with

$$\mathbf{R}_{\mathbf{sr}}(M) = \frac{1}{M} \sum_{m=0}^{M-1} \mathbf{s}(m) \mathbf{r}^H(m) \quad (19)$$

$$\mathbf{R}_{\mathbf{ss}}(M) = \frac{1}{M} \sum_{m=0}^{M-1} \mathbf{s}(m) \mathbf{s}^T(m). \quad (20)$$

The number of required known data bits is equal to  $M$ . Note that DEMR algorithm cannot perform a TOA estimate until  $M \geq 2K$  for the existence of  $\mathbf{R}_{\mathbf{ss}}^{-1}(M)$  [7].

We define

$$\hat{\mathbf{B}} = [\hat{\mathbf{B}}_1 \quad \hat{\mathbf{B}}_2 \quad \dots \quad \hat{\mathbf{B}}_K]. \quad (21)$$

$\hat{\mathbf{B}}_k$  as the estimation of  $\mathbf{B}_k$  only corresponds the  $k$ th user. Hence, the multiuser problem converts to the a series of  $K$  single user problems. Let

$$\mathbf{a}_k(\tau_{k,q}) = \text{vec}[\mathbf{A}_k(\tau_{k,q})] \quad (22)$$

$$\hat{\mathbf{b}}_k = \text{vec}[\hat{\mathbf{B}}_k] \quad (23)$$

where  $\text{vec}[\cdot]$  denotes stacking the columns of a matrix on top of one another. We get

$$\mathbf{a}_k(\tau_{k,q}) = \begin{bmatrix} \mathbf{P}_1(p_{k,q}) \mathbf{c}_k \\ \mathbf{P}_2(p_{k,q}) \mathbf{c}_k \end{bmatrix}. \quad (24)$$

With the approximation that TOA is the integer multiples of  $T_c$ ,  $\mathbf{a}_k(\tau_{k,q})$  is the cyclic shift of  $\mathbf{a}_k(0)$  [7].

Due to the long repetition time of pulse, the TOA estimation of the  $k$ th user is simplified to [7]:

$$\{\hat{\tau}_{k,q}\}_{q=1}^{L_k} = \arg \max_{\{\tau_{k,q}\}_{q=1}^{L_k}} \frac{\sum_{q=1}^{L_k} |\mathbf{a}_k^T(\tau_{k,q}) \hat{\mathbf{b}}_k|^2}{\mathbf{a}_k^T(0) \mathbf{a}_k(0)} \quad (25)$$

$\{\hat{\tau}_{k,q}\}_{q=1}^{L_k}$  corresponding to the  $L_k$ -largest values of (25) are the estimations of the multipath components' time delays. The earliest one among  $\{\hat{\tau}_{k,q}\}_{q=1}^{L_k}$  is the TOA estimation of the user  $k$ . In the real environment, since the exact number of multipath components  $L_k$  is unknown, the X-max criterion is employed to detect the TOA [7]. X-max criterion proposed in [13] selects the TOA estimation of user  $k$  as the earliest  $\hat{\tau}_{k,q}$  among  $\{\hat{\tau}_{k,q}\}_{q=1}^X$ .

### 3. SPREADING SEQUENCE GENERATION

As shown in section 2, the ranging performance of each user depends primarily on the cyclic autocorrelation property of the stacked code  $\mathbf{a}_k(0)$ . The number of users which can be supported by ranging system depends on the number of stacked codes  $\mathbf{a}_k(0)$ .

From (24), we can find that stacked sequence  $\mathbf{a}_k(0)$  consists of a sequence  $g_k(i)$  and an all-zero vector of the same length stacked above. Hence, the cyclic autocorrelation property of stacked code  $\mathbf{a}_k(0)$  is actually the non-cyclic autocorrelation property of  $g_k(i)$ . Since  $g_k(i)$  is formed by inserted  $N_c - 1$  "0" between each element in the spreading sequence  $c'_k(n)$ , the non-cyclic autocorrelation property of  $g_k(i)$  is formed by the non-cyclic autocorrelation function of  $c'_k(n)$  in the same way. Hence, the ranging performance of the DEMR estimator actually depends on the non-cyclic autocorrelation property of  $c'_k(n)$ .

In order to enhance the ranging performance of DEMR estimator, we introduce the binary chaotic sequences with good non-cyclic autocorrelation function to replace the Gold sequence. Moreover, unlike the Gold sequences which has finite number of sequences for a certain length, an ideally large number of chaotic sequences with good correlation property can be generated depending on the different initial conditions.

### 3.1. Chaotic sequence generation

Chaotic systems are deterministic nonlinear dynamical systems with sensitive dependence on the initial conditions. In this paper, we have selected spreading sequences generated by the Chebyshev map of degree 2 with  $x(0) \in (-1, 1)$  and the Tent map with  $x(0) \in (0, 1)$  as defined in [8].

$$x(n+1) = 2(x(n))^2 - 1, \quad |x(0)| < 1 \quad (26)$$

$$x(n+1) = \begin{cases} 1.8x(n) & \text{if } x(n) < 0.5 \\ 1.8(1-x(n)) & \text{otherwise.} \end{cases} \quad (27)$$

For each of the  $K$  users, an initial condition  $x_k(0)$  is chosen differently and independently. After passing through a quantization function (28) for Chebyshev map and (29) for Tent map, a set of binary chaotic spreading sequences is obtained.

$$F_C(x_k(n)) = \begin{cases} 1 & \text{if } x_k(n) > 0 \\ -1 & \text{otherwise} \end{cases} \quad (28)$$

$$F_T(x_k(n)) = \begin{cases} 1 & \text{if } x_k(n) > 0.5 \\ -1 & \text{otherwise} \end{cases} \quad (29)$$

### 3.2. Selection of binary Chaotic sequence

In this section, a detailed description of the method adopted to the selection of spreading sequences from a large number of sequences generated by (26)(28) or (27)(29) is given. Since the ranging performance depends on the non-cyclic autocorrelation function of spreading sequences  $c'_k(n)$ , a set of sequences with good non-cyclic autocorrelation function are selected from a large group of binary chaotic sequences. The non-cyclic autocorrelation function of spreading sequences is defined as

$$\rho_k(\tau) = \sum_{n=0}^{N-1-\tau} c'_k(n)c'_k(n+\tau). \quad (30)$$

We first consider the  $N+2$  Gold sequences of the length  $N$ . The non-cyclic autocorrelation function of the Gold sequences is calculated. We define  $\rho_k, k = 1, 2, \dots, N+2$  as the maximum absolute value of the sidelobe of non-cyclic autocorrelation function.

$$\rho_k = \max(|\rho_k(\tau)|) \quad \tau \neq 0, \quad k = 1, 2, \dots, N+2 \quad (31)$$

then let

$$\rho_G = \min(\rho_k) \quad k = 1, 2, \dots, N+2. \quad (32)$$

For a large pool of binary Chebyshev or tent sequences, non-cyclic autocorrelation function is first calculated for each sequence. Then, we group the sequences whose maximum absolute value of autocorrelation sidelobe is lower than  $\rho_G$ . Finally, these coarsely chosen sequences are sorted by increasing maximum absolute value of their autocorrelation sidelobe. The first  $K$  binary chaotic sequences are selected as the selected spreading sequence  $c'_k(n)$ .

## 4. NUMERICAL EVALUATIONS

Simulations have been carried out on the IEEE 802.15.4a channel mode 1 (CM1) channel to evaluate the performance of chaos-based DEMR estimator. Performance is evaluated by root mean square error (RMSE) of TOA estimation.

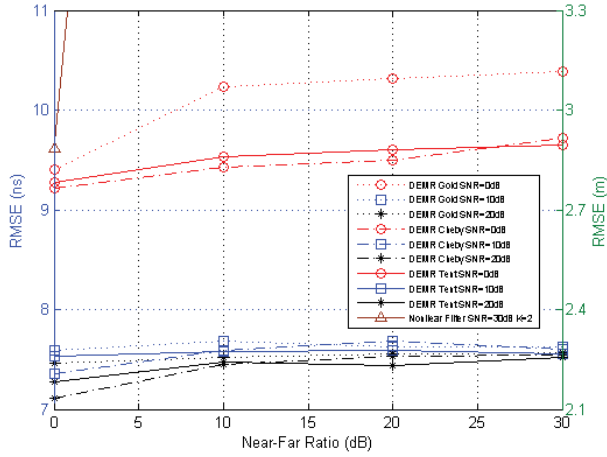
Each user is assigned a spreading sequence of length  $N = 31$  for both chaotic sequences and Gold sequence. TOA of the first user is evaluated. When using Gold sequences as spreading codes, sequence with autocorrelation parameter  $\rho_G$  is assigned to user 1. With no loss of generality, transmitted power of user 1  $P_1 = 1$ . All interfering users are given a random received power with a log-normal distribution with a mean  $d$  dB above the desired signal and a standard deviation equal to 10dB. That is  $P_k = 10^{\varepsilon_k/10}$ , where  $\varepsilon_k \sim N(d, 100)$ . The near-far ratio is defined as the ratio of the mean of the random powers of the interfering users to that of the power of user 1. Hence, the near-far ratio is  $d$  in dB. SNR is defined to be  $E_b/N_0$ , where  $E_b$  is the energy per bit for the first user. The pulse  $p(t)$  is a raised cosine pulse with roll-off factor  $\beta = 0.6$ , pulse and chip duration are set equal to 1ns, i.e.,  $T_c = T_p = 1ns$ ,  $N_c$  is taken equal to 16. Time delays of the first path of all the users are uniformly distributed over  $[0, 100ns)$ , which are the real-valued actual delays including a fractional part. In the CM1 channel,  $X$  is chosen to be 3. The results below are based on 500 Monte-Carlo trials.

We compare the ranging performance of chaos-based DEMR estimator with Gold-based DEMR estimator and the Nonlinear filter estimator. The Nonlinear filter estimator is proposed in [4] as a low complexity TOA estimator working at sub-Nyquist sampling rate. It performs nonlinear filtering on the energy of the received signal to mitigate MUI for the energy detection (ED) based estimator. In our simulations, Nonlinear filter estimator works at the chip sampling rate.

In Fig. 1, we show the RMSE performance as the function of the Near-Far ratio for different SNR in the CM1 channel. As shown in Figure 1, Nonlinear filter estimator has no robustness to near-far ratio. By contrast, near-far problem appears to have little effect on chaos-based DEMR estimator. Comparing with Gold-based DEMR, the use of selected chaotic sequences enhances the ranging performance further.

In Fig. 2, two sets of 41 selected chaotic sequences of length 31 are generated by Chebyshev map and Tent map, respectively. We assign these two sets of the chaotic sequences to  $K=41$  users and compare the RMSE of chaos-based DEMR with that of Gold-based DEMR and Nonlinear filter as the function of  $K$ . In chaos-based DEMR, since the selected chaotic sequences have lower autocorrelation sidelobe than that of Gold sequences, ranging performances are improved for all SNR. For the two higher SNR, RMSE of chaotic sequences with 41 users is still lower than that of Gold sequences with 31 users. For Nonlinear filter, RMSE soars to 25ns when  $K$  varies from 1 to 2. It is shown that DEMR estimator with selected binary chaotic sequences increases the



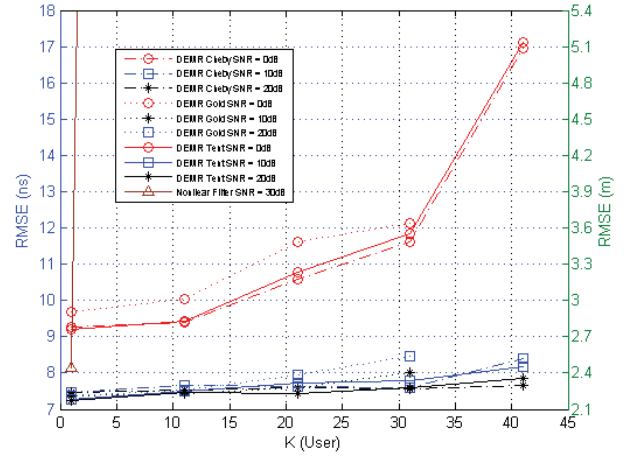


**Fig. 1.** RMSE versus near-far ratio for different SNR values with  $M = 100$ ,  $N = 31$ , and  $K = 10$  in CM1 channel.

system capacity and improves the ranging accuracy.

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**Fig. 2.** RMSE versus  $K$  for different SNR values with  $M = 100$ ,  $N = 31$ , and near-far ratio is 10 dB in CM1 channel.

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